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Citation: *Journal of Applied Physics* **116**, 163909 (2014); doi: 10.1063/1.4900537

View online: <http://dx.doi.org/10.1063/1.4900537>

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## Magnetic interactions in CoCrPt-oxide based perpendicular magnetic recording media

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(Received 27 August 2014; accepted 16 October 2014; published online 28 October 2014)

First order reversal curves (FORC) method has been reported to be an efficient tool to study interaction between grains and layers of magnetic materials. Although a few studies have been carried out on perpendicular recording media in the past, a study on the effect of systematic variation of exchange interaction in granular perpendicular magnetic recording media on FORC contours has not been carried out in detail. Such a study will help to understand the use of FORC better. In this paper, we have made a systematic set of samples in order to study the variation in exchange coupling and its effect on FORC contours. The pressure during the deposition of the second ruthenium layer and the magnetic layer was varied to alter the separation between the grains and hence the exchange interaction between the grains in the CoCrPt-oxide recording layer. In addition, the thickness of Co-alloy cap layer was used as an additional tool to control the exchange interaction between the magnetic grains. The results indicated that the interaction field obtained from the FORC does not vary in a significant manner when the changes in exchange interaction are small. In comparison, the peak intensity of the FORC shows a clear trend as the exchange coupling is varied, making it a more suitable parameter to study the exchange and magnetostatic interactions in systems such as magnetic recording media. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4900537>]

### INTRODUCTION

Hard disk drives have been using thin film recording media since 1990s.<sup>1</sup> Current hard disk media make use of CoCrPt alloys segregated using certain or several kinds of oxide materials at the grain boundary.<sup>2,3</sup> An important understanding that helped to improve the recording performance of media was the fact that the exchange coupling plays an important role in the noise performance.<sup>4,5</sup> While the earlier generation of thin film recording media exhibited a very strong transition noise, understanding of the exchange coupling between the grains helped to improve the recording performance. In the era of longitudinal media, segregants such as Cr, Ta, and B were co-deposited along with the CoPt alloy in order to form grain boundaries.<sup>6,7</sup> These grain boundaries provided the required exchange decoupling between the grains and hence to reduce the noise.<sup>8,9</sup> In granular perpendicular recording media, oxides such as SiO<sub>2</sub>, TiO<sub>2</sub> are used to form the grain boundary region.<sup>10,11</sup> Even in the FePt media, which are investigated for future heat-assisted magnetic recording applications, segregants such as C, SiO<sub>2</sub> are being used.<sup>12,13</sup> Irrespective of the materials (FePt or CoCrPt-oxide) used for recording media technology, an understanding of exchange interaction between them is important to improve the recording performance.

During the early 2000, Honda *et al.* have carried out simulations and proposed that some amount of exchange coupling is beneficial in the signal-to-noise performance of perpendicular recording.<sup>14</sup> Experimentally, media designs

with capped layers became crucial in achieving improved performance, such as reduced switching field distribution, high signal-to-noise ratio (SNR), etc.<sup>15</sup> Wang and Zhu pointed out that the grains in a recording medium may have a distribution in exchange interaction if they are not processed well. They concluded that a high pressure deposition along with suitable materials as segregants is necessary to completely decouple the grain.<sup>16</sup> This observation further confirms the need for a capping layer to induce exchange coupling. Over the years, it has been well understood that the knowledge of magnetic interactions present in a recording medium is crucial to improve its performance.<sup>17</sup>

In the recording media industry, the noise performance may be tested with spin-stands. As noise also could arise from various other sources, such as c-axis dispersion etc., it is sometimes useful to correlate the SNR performance with other measurements in order to obtain better insight. Therefore, researchers have used various techniques to understand the interactions in magnetic recording media. In the era of longitudinal recording, delta-M method was commonly used.<sup>18</sup> Quite recently, first-order reversal curves (FORC) are considered to gain understanding on the interactions present in the system.<sup>19,20</sup> Papusoi *et al.* have carried out a systematic investigation on FORC of recording media and indicated that FORC is useful to measure switching field, demagnetization factor, and interaction field independently.<sup>21</sup> Yin *et al.* have carried out simulation and experimental work and have indicated that the interaction field becomes negative when the exchange coupling is increased.<sup>22</sup> However, they have used only two samples in their experimental study, which have strikingly different characteristics. In order to obtain meaningful information about interactions in recording media, where

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Set A	Set B
a-CH <sub>x</sub> /CN <sub>x</sub>	a-CH <sub>x</sub> /CN <sub>x</sub>
Co-alloy Cap layer (0, 3, 6 nm)	Co-alloy Cap layer (0, 3, 6 nm)
CoCrPt-Oxide (15nm) P = 40 mTorr	CoCrPt-Oxide (15nm) P = 20 mTorr
Ru <sub>2</sub> (10nm), P = 55 mTorr	Ru <sub>2</sub> (10nm), P = 25 mTorr
Ru <sub>1</sub> (10nm)	Ru <sub>1</sub> (10nm)
Ta (5 nm)	Ta (5 nm)

FIG. 1. Schematic illustration of sample structures used in this study. Cap layer thickness was varied from 0 to 6 nm and the sputter gas pressure during the deposition of Ru<sub>2</sub> and CoCrPt-oxide was varied for samples in set A and set B as shown.

the samples may have only a slight variation between them, we have fabricated a systematic set of samples where the interaction between the grains was varied through the layer structure and have carried out the investigations on interactions.

## EXPERIMENTAL

The recording media samples were prepared by DC magnetron sputtering using production type Intevac Lean 200 sputtering machine. Figure 1 shows the schematic illustration of the samples made for this study. Typical seedlayers such as Ta and Ru required for the textured growth of Ru(00.2) and Co(00.2) were used. The soft underlayers were not deposited purposely, in order to measure FORC using alternating gradient force magnetometer (AGM). The first Ru layer (Ru<sub>1</sub>) was deposited at about 5 mTorr. This layer, deposited at high mobility conditions, helps in achieving the desired hcp(00.2) texture. The second Ru layer (Ru<sub>2</sub>) was deposited at various values of pressures higher than that of Ru<sub>1</sub>. We have reported a dual-Ru structure earlier and pointed out that the higher pressure deposition causes isolation of Ru grains, along with a higher pressure deposition of the CoCrPt layers, results in exchange decoupling.<sup>23</sup> Therefore, the deposition pressure of Ru<sub>2</sub> and the recording layer were varied to alter the exchange interaction between the grains. These two layers were fabricated at higher deposition pressures in order to achieve the desired grain morphology. It has been well understood that the segregation of recording media depends on the sputter gas pressure during the deposition of these two layers.<sup>24</sup> Media in sample set B were made with comparatively lower pressures for the Ru and CoCrPt-oxide layers than those samples in set A. Media layers were also made with and without capping layer in order to fine-tune the exchange coupling.<sup>25</sup> X-ray diffraction was carried out to understand the crystallographic properties. The targets used in the study have typical composition as in the current technology and the trend in the results reported here are expected to be reproducible by hard disk media researchers, irrespective of slight differences in the composition.

FORCs were measured using AGM. At first, the samples were saturated using a large positive field (about 16 kOe). Then the field was swept to a reversal field  $H_r$ . The magnetization  $M(H_r, H_a)$  was measured at each field step,  $H_a$ . The magnetization curve that results when applied field ( $H_a$ ) is increased from  $H_r$  back to saturation is defined as the FORC. This measurement is repeated for different reversal fields

depending on the number of reversal loops. The FORC contour, which can be obtained as reported earlier,<sup>26</sup> was plotted as a function of  $H_u$  and  $H_c$  as y and x axes, respectively.  $H_u$  is commonly defined as the interaction field and  $H_c$  is the switching field respectively, where  $H_u = (H_r + H_a)/2$  and  $H_c = (H_a - H_r)/2$ .

## RESULTS AND DISCUSSION

Figure 2 shows the XRD  $\theta$ - $2\theta$  scans of the samples. Set A represents the samples deposited at a sputtering gas pressure of 55 mTorr for Ru<sub>2</sub> and 40 mTorr for the recording layer. Set B corresponds to 25 mTorr for Ru<sub>2</sub> and 20 mTorr for the recording layer. It can be noticed that the samples with no cap layer show no distinct Co(00.2) peak, but as a shoulder at higher angles of Ru(00.2) peak. As the cap layer thickness is increased, the Co(00.2) peak appears distinctly. The  $\Delta\theta_{50}$ , obtained from the rocking curves, show a slight decrease (0.05 degrees) with the cap layer thickness. As such a decrease is marginal, the changes in magnetic properties arising from the introduction of cap layer are not due to the changes in the texture.

Figure 3 shows the hysteresis loops of recording media, deposited at two different pressures. It can be noticed from Figures 3(a) and 3(b) that the set A samples deposited at higher pressure have a higher coercivity, in general. In addition, the sample without cap layer (0 nm) has a low nucleation field and a broad switching characteristic. When a cap layer is introduced, nucleation field was found to increase

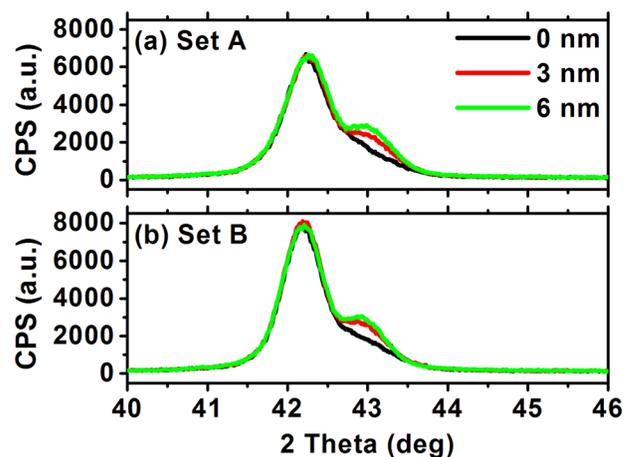


FIG. 2. XRD  $\theta$ - $2\theta$  scans of set A and set B samples for different cap layer thickness.

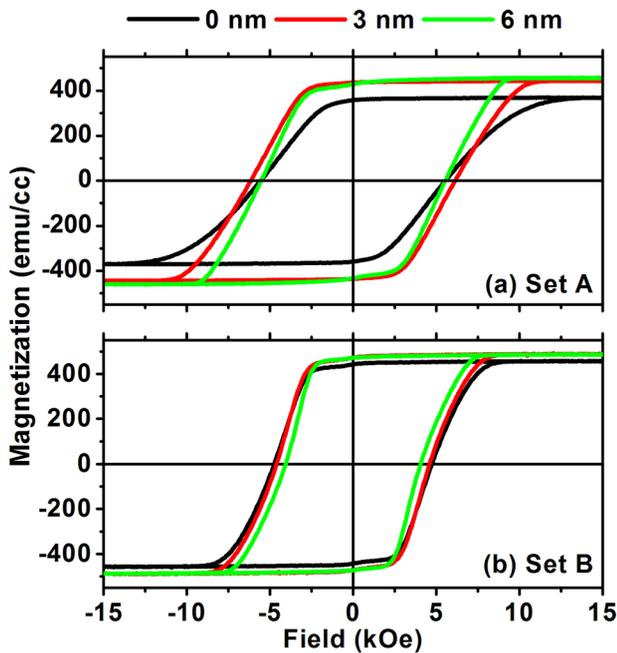


FIG. 3. Hysteresis loops of (a) set A samples ( $\text{Ru}_2 - 55$  mTorr, RL - 40 mTorr) and (b) set B samples ( $\text{Ru}_2 - 25$  mTorr, RL - 20 mTorr) for various thickness values of the cap layer.

and the slope of the hysteresis loop increased with the cap layer thickness, indicating that the cap layer enhanced the exchange coupling between the grains. These results are well known to those working in the field of perpendicular recording media. Enhancement of exchange coupling by capping layers in perpendicular media is well documented.<sup>27,28</sup> The coercivity in this set of samples shows an initial increase followed by a decrease with the cap layer thickness. Such an increase of coercivity with cap layer thickness has also been observed by Nemoto *et al.*<sup>29</sup> From the results of Nemoto *et al.*, it appears that the trend of coercivity appears to depend on the product of saturation magnetization and thickness ( $M_s \cdot t$ ) of the cap layer. An increase of  $H_c$  with capping layer is observed in samples with lower values of  $M_s \cdot t$  and  $H_c$  decreases for larger values of  $M_s \cdot t$  either due to thickness or due to  $M_s$  for the same value of  $t$ .

It can also be noticed from Figure 3(b) that the nucleation field does not change significantly in set B samples and that the coercivity reduces as the cap layer thickness was

increased. The reduction of coercivity with the increase of cap layer thickness and the increase in slope of the hysteresis loops in Figure 3(b) are indications of increasing exchange coupling.<sup>27</sup> The loop shape of sample with a 6 nm cap layer thickness, where the moment drops sharply until coercive field and reduces at a slower rate is very similar to the loops observed in samples where exchange coupling was higher.<sup>30</sup> These results, which are in agreement with earlier observations, indicate that the exchange coupling increases in these samples as the capping layer thickness is increased or as the sputter gas pressure is reduced. These results are well understood in the literature on perpendicular media. In a deposition process that was carried out at high pressure without capping layer, the grains are well decoupled and hence their exchange coupling is weak or negligible. However, when a capping layer is introduced, it offers a spatially uniform intergranular exchange coupling.<sup>31</sup> The cap layer thickness in both the set of samples leads to a decrease in the saturation field, and as a result a decrease in the switching field distribution. Results observed in Figures 3(a) and 3(b) are typical for samples where the exchange coupling is increased at low pressure deposition or with the increase in the cap layer thickness.<sup>15,23</sup> These results illustrate that the samples fabricated for this study offer a good platform to understand the changes in the magnetic interaction using alternative techniques such as FORCs.

Figure 4 shows the FORC contours of set A samples. It can be noticed that the FORC contours of all the samples are elongated along the  $H_u$  axis and that there is a change in the shape with cap layer thickness. The intensity of the contours increases and the broadening of the contour reduces, as the thickness of the cap layer is increased. The peak position along the  $H_c$  axis varies from about 5000 Oe to 6000 Oe, in agreement with the trend of coercivity. The interaction field ( $H_u$ ) at which the contour peaks along the  $H_u$  axis also moves from about 2200 Oe towards zero, as the thickness of the cap layer is increased. Such a reduction in the  $H_u$  is an indication of an increase in exchange coupling, as reported in previous works.<sup>32</sup>

Figure 5 shows the FORC contours of set B samples. In a similar fashion to set A samples, the FORC contours of set B samples are also found elongated along the  $H_u$  axis but the extent of elongation is not as significant as in set A samples. The intensity of the contours is stronger than that in the set A

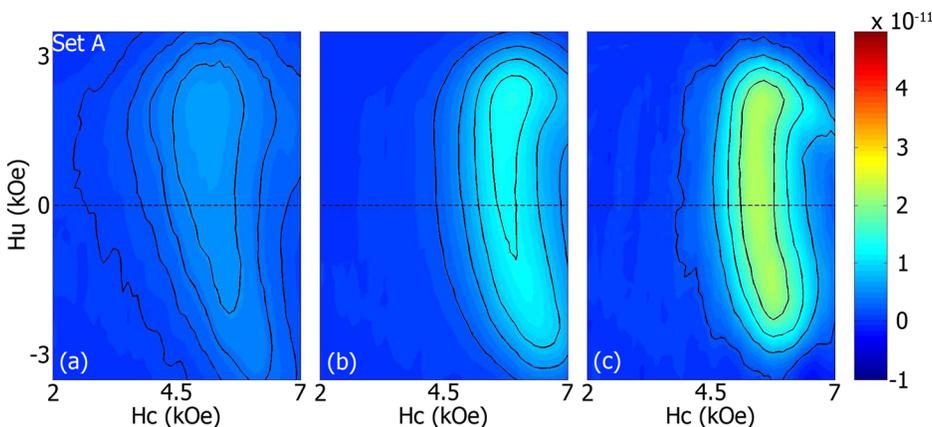


FIG. 4. FORC contours of set A samples for various values of cap layer thickness (a) 0 nm (b) 3 nm and (c) 6 nm.

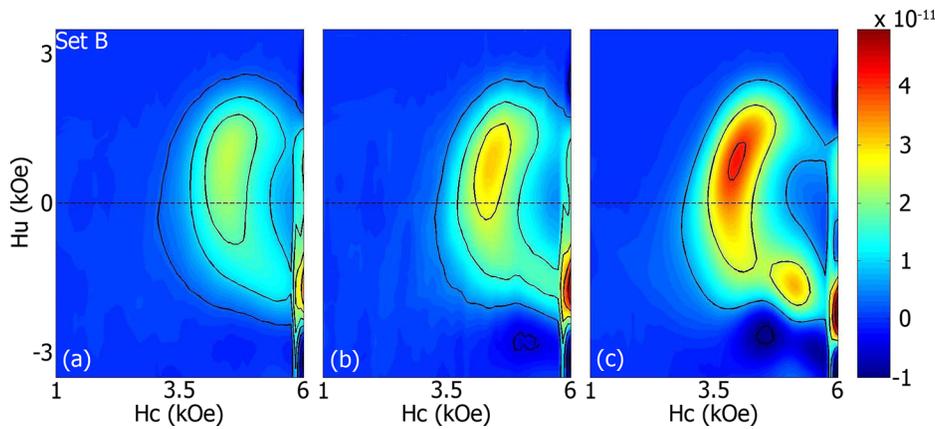


FIG. 5. FORC contours of set B samples for various values of cap layer thickness (a) 0 nm (b) 3 nm and (c) 6 nm.

sample, even when there is no cap layer. The intensity of the contour increases significantly, as the thickness of the cap layer is increased. The interaction field ( $H_u$ ) however does not change significantly as in the set A sample, as the thickness of the cap layer is increased.

In the literature on FORC, a movement of  $H_u$  towards negative direction or an increase in the peak intensity has been reported to be signs of an increased exchange coupling.<sup>25</sup> Therefore, in order to understand which parameter from FORC can give a clear indication of the changes in exchange coupling, we have measured coercive squareness  $S^*$  from hysteresis loops, and the  $H_u$  and peak height of FORC contours for all the samples.  $S^*$  has been used to gauge the exchange coupling and is defined as  $S^* = 1 - M_r / (H_c * dM/dH)$ , where  $M_r$  is the remanent magnetization,  $H_c$  is the coercivity, and  $dM/dH$  is the slope at the coercive point.<sup>9</sup>

Figure 6 shows the trend of these parameters for the set A (higher pressure) and set B (lower pressure) samples. It can be noticed from Figure 6(a) that the set A samples show expected trends: The value of  $S^*$  is very low (about 0.3) in the absence of cap layer, indicating the absence of exchange coupling between the grains.  $S^*$  increases with the thickness of cap layer due to the increase in the inter-granular exchange coupling, as provided by the capping layer. The

value of  $H_u$ , although is prone to measurement inaccuracies, shows a decrease for thicker cap layer (6 nm), in comparison to the sample with no cap layer. As mentioned in previous studies on FORC, such a decrease of  $H_u$ , which indicates an increase of exchange coupling, correlates with the observation of  $S^*$ . Figure 6(b) shows similar parameters for samples deposited at lower pressure. The value of  $H_u$  in lower pressure sample with no cap layer is lower than that of higher pressure sample, indicating that set B samples as a whole have a higher exchange coupling than set A samples.  $H_u$  also shows a slight reduction as the cap layer thickness increases. These results support earlier observations that the position of contour along  $H_u$  axis may be considered for understanding the changes in exchange interaction between the samples. However, for the set B samples, the changes in  $H_u$  as well as  $S^*$  as a function of cap layer thickness are not significant. A lower value of  $H_u$  and a higher  $S^*$  indicate that the exchange coupling in this set of sample is, in general, higher than that in set A. Nevertheless, the change in exchange coupling cannot be seen from  $S^*$  or  $H_u$ .

In addition to  $S^*$  and  $H_u$ , Figures 6(a) and 6(b) also show the contour peak heights for different samples. It can be noticed that the peak height shows a clear trend as a function of cap layer thickness, in both the set of samples. The peak height of set B (lower pressure) sample also shows a larger value than that of set A (higher pressure) sample. These results indicate that the contour peak height may be a better quantitative figure to monitor changes in the exchange interaction which may be difficult to be recognized using typical hysteresis loop measurements (such as  $S^*$ ), particularly when the exchange coupling is very strong.

The rationale for the fact that the contour peak height is a better parameter can be explained as follows; When the exchange coupling is increased, either by a cap layer or through the process of making less-granular medium, the reversal mechanism changes from “reversal of magnetization of individual grains” to the one that involves a “collective magnetization reversal”. It is well known that the coercivity in the case of individual grain reversal is primarily determined by the  $H_k$  of the grains. On the other hand, the coercivity in the case of collective magnetization reversal is usually less as it is initiated by the reversal of the weakest region. Moreover, the change in the magnetization with respect to the applied reversal field ( $dM/dH$ ) in the case of

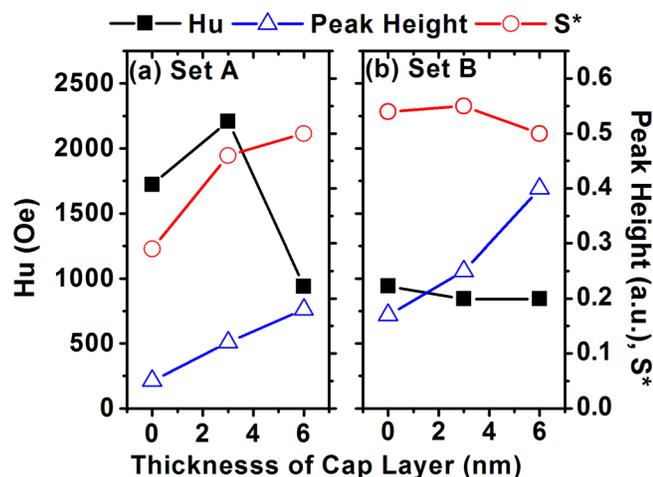


FIG. 6.  $H_u$  and peak height from FORC contours of set A samples and set B for various values of cap layer thickness. The value of  $S^*$ , obtained from the hysteresis loop, is also given.

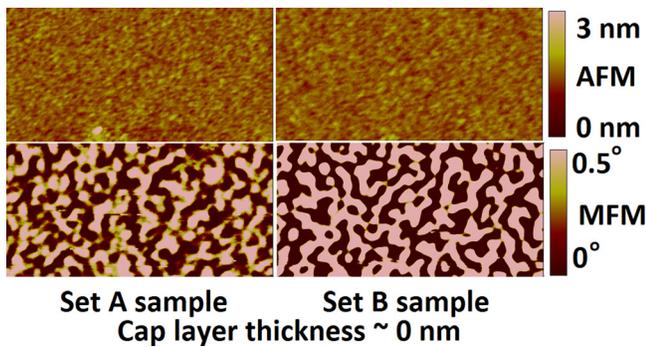


FIG. 7. AFM (top) and MFM (bottom) images of typical set A (left) and set B (right) samples.

collective magnetization is sharper.  $S^*$ , by definition, is related to the product  $H_c^* dM/dH$ . Therefore, the changes in  $S^*$  may not be significant, if  $H_c$  changes drastically, as in the set B samples. On the other hand, FORC contour peak height involves mixed double derivative of  $M$  with respect to reversal field ( $H_r$ ) and applied field ( $H_a$ ) and does not involve  $H_c$ . Therefore, FORC contour peak height indicates the increase in exchange coupling without the drawbacks, associated as in  $S^*$ . The fact that the  $H_u$  is not significantly useful is because the changes in  $H_u$  are smaller, as compared to the spread of the FORC contour.

In order to strengthen the understanding on the contour peak height further, we have carried out magnetic force microscopy (MFM) and correlated peak height with the “magnetic roughness.”<sup>33</sup> Magnetic roughness measures the variation in the magnetic flux (as measured by phase angle) with respect to a baseline. In the absence of exchange coupling, each grain is an independent magnetic unit and hence the cluster size will be same as the grain size. Most likely, in such a case, MFM cannot resolve the grains and the resultant image will be the base noise of the system. On the other hand, in the presence of exchange coupling, clustering will occur leading to magnetic stray fields from a group of grains. MFM will pick up such stray fields and the image will show a roughness. MFM roughness has hence been reported to be an indicator of the exchange coupling and the resultant cluster formation.<sup>33</sup> Increase in exchange coupling increases the MFM roughness as well as the noise of the recording media. Therefore, understanding the correlation of FORC contour peak height and  $S^*$  with MFM roughness is useful to further validate the FORC parameters.

With this thought in consideration, MFM images of the samples were captured at the ac demagnetized state at a scan height of 10 nm. Figure 7 shows the AFM and corresponding MFM images of a typical set A and Set B samples. It can be noticed that the AFM topography is distinctly different from that of the MFM images—indicating that the MFM signal does not arise due to topographic variations. It can also be noted that the samples in set A and set B show different magnetic contrasts. The sample in set B show a higher contrast and well-connected domain patterns indicating a higher exchange coupling in set B samples. From the MFM images, “roughness” was estimated as reported by Glijer *et al.*<sup>33</sup>

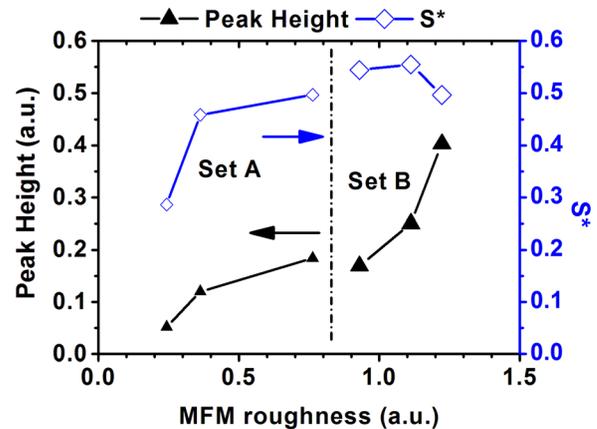


FIG. 8. Correlation of contour peak-height (filled triangles) and  $S^*$  (open diamonds) with the MFM roughness for samples in set A (smaller symbols) and set B (bigger symbols) (Separated by the dotted line).

Figure 8 shows such a graph of  $S^*$  and FORC peak height for all the samples in this study. It can be noticed that  $S^*$  in set A samples increases with MFM roughness, indicating the expected correlation between  $S^*$  and the magnetic roughness. In the case of set B samples, magnetic roughness increases but  $S^*$  does not show an increase. This indicates that  $S^*$  may not always be a good indicator of exchange coupling. On the other hand, the FORC contour peak height shows an increase with MFM roughness. Such a good correlation between FORC contour peak height and MFM roughness further confirm the usefulness of FORC contour peak height in understanding the exchange interactions of recording media.

## CONCLUSIONS

Various characterization techniques, such as magnetometry, magnetic force microscopy and first order reversal curves have been employed to correlate and understand the exchange interaction in granular perpendicular magnetic recording media. It was found that the  $S^*$ , which has been used as an indicator of exchange coupling, cannot be relied on completely. FORC contour peak height was found to increase with exchange coupling and is proposed as a suitable parameter to monitor the changes in the exchange coupling of recording media. The MFM roughness, which is an indicator of exchange coupling, also correlates very well with the FORC contour peak height and support the fact that the relative changes in FORC contour peak height may be used to understand the trend in exchange coupling.

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